

Multiphase flow in complex fracture apertures under a wide range of flow conditions

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At several DOE sites and in other countries, pollutants have traveled in the vadose zone much further and faster than predicted. This observation reveals the inadequacies of both computer models used to predict the transport of pollutants in the subsurface and the conceptual models on which they are founded. We propose filling important knowledge gaps and developing new conceptual models to understand how pollutants travel in the vadose zone. We have planned a closely coordinated experimental and computer modeling program to study multiphase flow in fracture apertures. We will test the hypothesis that focusing flow onto preferred pathways (such as fracture apertures), intermittent flow condition, and the colloid-mediated transport of strongly-adsorbed pollutants play an important role in rapidly transporting subsurface contamination. We will perform experiments and simulations using several modeling methods, both under a wide range of flow conditions in realistic, complex well-characterized apertures (computer-generated fracture apertures using both fractal and non-fractal statistical models, well-characterized natural fractal apertures and/or replicas of natural fracture apertures). Our modeling program will be based on methods that are well suited to geometrically complex boundary conditions (realistic fracture aperture geometries) and complex moving interfaces. These methods include lattice-gas/lattice-Boltzmann models, invasion percolation models, molecular dynamics and smoothed particle hydrodynamics. By using these various methods, we can evaluate different modeling approaches and use computer modeling to extrapolate and interpolate the experiments to a broader range of conditions. We will perform the experiments in a unique and versatile matched-index-of-refraction flow laboratory at INEEL.

To illustrate the desirability of refractive-index matching when fill material is present within a simulated fracture, an idealized fracture (a Hele-Shaw cell) was constructed using the materials that we plan to employ. The fill material consisted of quartz particles with a wide range of shapes and sizes, and with a maximum dimension approximately that of the gap width. The quartz particles occupy most of the cell. Mineral oil was then injected at one location on top of the quartz particles, and the invasion of the oil was recorded. Two images recorded several minutes apart are presented in Figure 1. The ruled lines drawn on a light diffuser placed behind the cell are clearly visible in regions in which the fill material is saturated with oil and are not visible in regions in which the fill material is not saturated. The oil-quartz interfaces effectively disappear. The bounding oil-air interface is visible in the original photographs (but not in the scanned images shown), as are regions (bubbles) of defending fluid (air). One sees that when indices are not matched, the transparent porous material is effectively opaque (Figure 1a).

The direct observation of fluid flow phenomena in complex fracture apertures obtained using the MIR technique can provide essential information required for the development of the conceptual models that are needed to understand and model subsurface transport processes. The ability to measure 3-D Eulerian velocity fields in complex passageways is clearly an advantage of matching the index of refraction of the fluid and the material surrounding the passageways. If the simulated fracture walls are not flat, then the wall must be index matched for an undistorted view of the fracture interior. This observation is especially true if quantitative measurements are required. Laser Doppler velocimetry (LDV) will not be practical unless the indices of refraction of the walls, fill material and oil are closely matched.

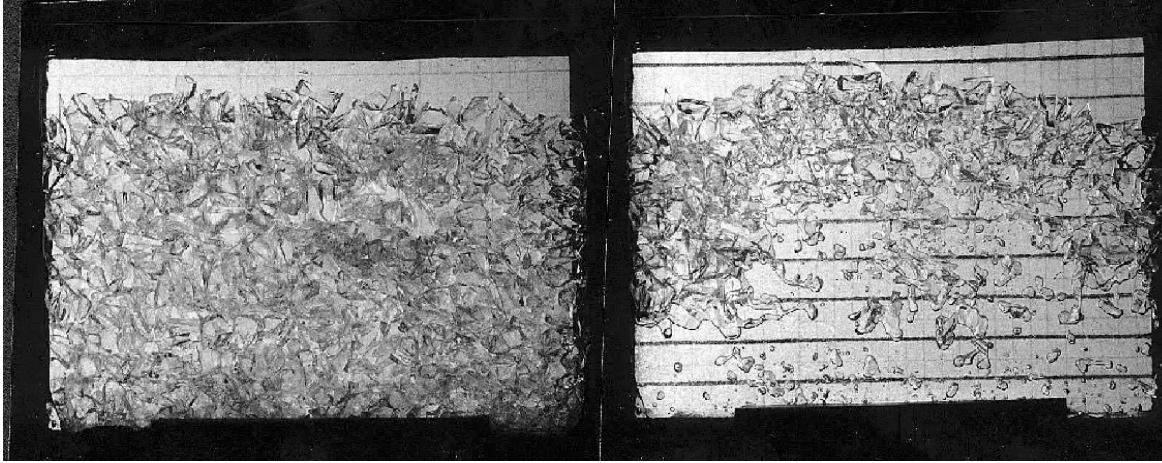


Fig. 1. Refractive-index matching of fill material in an idealized fracture aperture during invasion of a refractive index matched liquid (a) the cell contains only fill, (b) the cell is partly filled with liquid, which has been injected near the top of the cell.

A conceptual experiment for a simulated fracture (with and without fill material) is sketched in Figure 2. Potential instrumentation includes:

- *Three-dimensional particle tracking velocimeter (3D-PTV)* to measure front passage, particle transport (flow velocities) and motion of bubbles. The technique uses tracer particles, which must be sufficiently small to accurately follow the flow but large enough to minimize the effects of diffusion.
- *Laser Doppler velocimeter* (not shown) for measurements of transient pointwise velocity components in the index-matching liquid. A two-velocity component LDV and associated three-dimensional positioning system is available for use on the MIR flow loop.
- *High resolution CCD (digital) camera* and/or video camera photography to examine details of the motion of tracer particles in the fluid and of the gas-liquid interface.
- *Low magnification video images* to track the liquid-gas interfaces. Interface movement may be tracked using software to analyze digitized video images.
- *Observations of liquid levels* in the inlet fluid reservoir to determine the total flow rates.

Phase displacements, phase interface geometry, liquid flow and particle transport may be studied. Mounting the simulated fracture cell in the MIR flow loop permits use of the existing two-dimensional LDV and the associated three-dimensional computer-controlled traverse. The flow loop also provides the fine temperature control necessary for laser velocimetry measurements. The simulated fracture aperture plus instrumentation would be mounted on a frame capable of rotation around the horizontal axis to permit orientation of the fracture at any angle between horizontal and vertical.

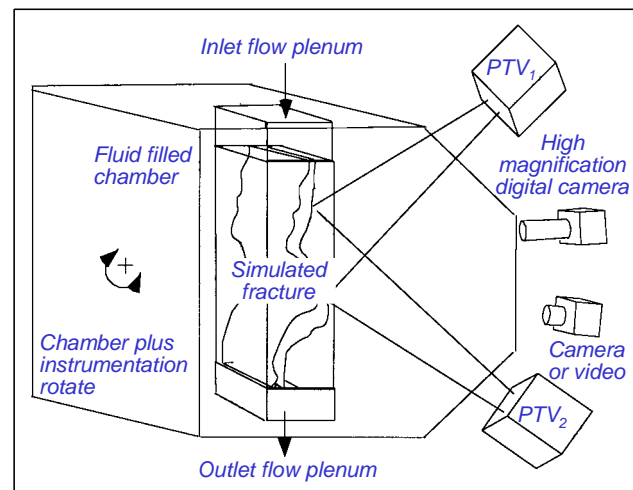


Fig. 2. Conceptual design of transient flow experiment to examine phase displacements, flow and colloidal particle transport in a fracture.

